

CHARM CORRELATION AS A DIAGNOSTIC PROBE OF QUARK MATTER

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Abstract

The use of correlation between two open-charm mesons is suggested to give information about the nature of the medium created in heavy-ion collisions. Insensitivity to the charm production rate is achieved by measuring normalized cumulant. The acollinearity of the D momenta in the transverse plane is a measure of the medium effect. Its dependence on nuclear size or E_T provides a signature for the formation of quark matter.

The conventional probes of quark matter in heavy-ion collisions, such as dileptons and J/ψ suppression, have not provided conclusive evidence about the creation or absence of quark-gluon plasma [1]. A large part of the difficulties involve the ambiguities arising from competing processes and from uncertainties in the initial normalizations of some key quantities. An effective probe should be free of such ambiguities. In this paper we suggest the possibility that charm correlation may be such a probe.

The correlation proposed is between open-charm mesons at nearly opposite directions. The charm quark is used both for tagging and for probing. Heavier quark can be used when appropriate; charm will be used as a generic term for heavy quark in the following discussion. Lighter partons and associated minijets are too copiously produced at RHIC and LHC [2] to be useful for our purpose of tagging and probing. The idea is based simply on the dual requirements that the signature should be independent of the production rate but sensitive to the medium through which the probe traverses. Appropriately normalized cumulant can satisfy the first requirement, while the transverse deviation from exact back-to-back correlation meets the second.

Briefly stated, it is suggested that one searches for $D\bar{D}$ produced in the transverse plane at $y = 0$ with their momenta nearly collinear, but opposite. The acollinearity in the transverse plane is the measure of interest. To enhance the effect, experimental cuts should be made on the magnitudes of the D -meson momenta so that they are nearly equal and not too large. We expect that the mean acollinearity is smaller if the medium is deconfined quark matter than if it is not.

The proposed measure is similar in spirit to the acoplanarity of jets suggested by Appel [3], but significantly different in substance. The major differences are: (a) the jet axes cannot be as precisely determined as the D -meson momenta, (b) at high energy too many jets are produced resulting in contamination and deterioration of the correlation signal, (c) we emphasize the difference between the propagation of a c quark through a deconfined medium and that of a D -meson through a confined medium, and (d) the phenomenology of $D\bar{D}$ correlation can reveal interesting physics even in kinematic regions where perturbative

QCD (pQCD) is unreliable.

Let \vec{p}_1 and \vec{p}_2 be the momenta of the two detected charge-conjugate D mesons. The cumulant is

$$c(\vec{p}_1, \vec{p}_2) = \rho_2(\vec{p}_1, \vec{p}_2) - \rho_1(\vec{p}_1)\rho_1(\vec{p}_2), \quad (1)$$

where ρ_n is the n -particle distribution function; it is the irreducible part of the two-particle correlation. In a heavy-ion collision the cumulant can in general be expressed in the form

$$c(\vec{p}_1, \vec{p}_2) = \int \frac{d^3k_1}{k_1^0} \frac{d^3k_2}{k_2^0} S(\vec{k}_1, \vec{k}_2) H(\vec{k}_1, \vec{p}_1) H(\vec{k}_2, \vec{p}_2), \quad (2)$$

where $S(\vec{k}_1, \vec{k}_2)$ is the probability of producing two partons with momenta \vec{k}_1 and \vec{k}_2 , and $H(\vec{k}_i, \vec{p}_i)$ is the hadronization function that connects the parton i at the point of creation to the hadron detected with momentum \vec{p}_i . Hereafter we adopt the convention of using the symbol k (p) for parton (hadron) momentum. It should be stressed that H is not simply the fragmentation function usually used for jet considerations because firstly the produced parton must traverse a dense medium and suffer momentum degradation before fragmentation, and secondly the hadronization process may be recombination [4, 5] instead of fragmentation. In fact, it has been shown that the data of open charm production in the forward region of hadronic collisions can be well described by recombination [6], but badly by pQCD or fragmentation model [7].

In the domain where pQCD is reliable one can write $S(\vec{k}_1, \vec{k}_2)$ for AB collision as

$$S(\vec{k}_1, \vec{k}_2) = c \int \frac{d^3k_a}{k_a^0} \frac{d^3k_b}{k_b^0} F_A(k_a) F_B(k_b) \delta^4(k_a + k_b - k_1 - k_2) |M(a + b \rightarrow 1 + 2)|^2 \quad (3)$$

plus other terms of similar structure, if more than one hard subprocess are important. In (3) c is a numerical constant, $F_A(k_a)$ is the parton distribution in nucleus A , and $M(a + b \rightarrow 1 + 2)$ is the amplitude of the hard subprocess involved. There is a great deal of physics contained in the determination of $F_{A,B}$, which depends on nucleon structure function at small x , gluon distribution, nuclear shadowing, initial-state radiation, preequilibrium and possibly thermal interactions, space-time evolution, etc. So much uncertainty is involved in the problem that the study of open-charm production has been suggested as a means to learn more about the

parton dynamics in the early phase of nuclear collision [8, 9], i.e., the reverse of using $F_{A,B}$ to predict measureable quantities. While that is certainly a worthwhile project to pursue, our proposal here is to circumvent all that complication and proceed with the use of $S(\vec{k}_1, \vec{k}_2)$ independent of the details about $F_{A,B}$.

From $S(\vec{k}_1, \vec{k}_2)$ not only can two-particle inclusive distribution be determined as in (2), the one-particle distribution can also be obtained as follows

$$\rho_1(\vec{p}_2) = \int \frac{d^3 k_1}{k_1^0} \frac{d^3 k_2}{k_2^0} S(\vec{k}_1, \vec{k}_2) H(\vec{k}_2, \vec{p}_2). \quad (4)$$

To free our signal from the uncertainties of the primordial parton dynamics, let us define the singly-normalized cumulant function

$$C(\vec{p}_1, \vec{p}_2) = c(\vec{p}_1, \vec{p}_2) / \rho_1(\vec{p}_2). \quad (5)$$

It is clear from (2) and (4) that $C(\vec{p}_1, \vec{p}_2)$ should be insensitive to the rate of charm production.

Hereafter we shall regard hadron 2 (with momentum \vec{p}_2) as the trigger particle, against which we study the properties of the probe particle 1. Of course, it is the relative momentum between the trigger and probe that is important, but conceptually it is efficient to identify (arbitrarily) one of the two D mesons as the trigger and define the axes such that the trigger momentum in every event is always aligned along a fixed direction, say $-\hat{x}$ axis, with \hat{y} being the axis normal to the scattering plane containing the beams and the trigger. The aim is to study the momentum distribution of the other D meson in the neighborhood of the $+\hat{x}$ axis.

Since the parton momenta \vec{k}_1 and \vec{k}_2 can have large longitudinal imbalance due to unequal momenta, \vec{k}_a and \vec{k}_b , of the initial colliding partons, but they can have only limited total transverse momentum $\vec{K}_T = \vec{k}_{1T} + \vec{k}_{2T}$ due to the small intrinsic transverse momenta of the initial partons and to the initial-state radiation, we can avoid the complexity of the full structure of $S(\vec{k}_1, \vec{k}_2)$ if we restrict \vec{k}_1 and \vec{k}_2 to only the near neighborhood of a common transverse plane. That is achieved by requiring that \vec{p}_1 and \vec{p}_2 lie only in the transverse plane at $y = 0$. For brevity we shall refer to that plane as \mathcal{T}_0 . Since we expect the angular

differences between \vec{k}_i and \vec{p}_i to be small, that requirement therefore forces \vec{k}_1 and \vec{k}_2 to be very close to \mathcal{T}_0 also.

The aim of this problem is to learn about the medium effect through $H(\vec{k}_i, \vec{p}_i)$, on which the measureable $C(\vec{p}_1, \vec{p}_2)$ depends. With \vec{k}_i near \mathcal{T}_0 those partons do not participate in the longitudinal expansion of the system, which is another area of large uncertainties. But even in \mathcal{T}_0 there are several possible processes leading from the partons (k_i) to the hadrons (p_i), each involving a different hadronization function $H(\vec{k}_i, \vec{p}_i)$. So far we have not specified the kinds of partons carrying k_i . They can be high-momentum quarks of the u and d types, or lower-momentum gluons, all capable of fragmenting into the D mesons. Since the two fragmentation processes are independent, \vec{p}_1 and \vec{p}_2 are not correlated even though \vec{k}_1 and \vec{k}_2 are. To narrow down the hadronization process we make use of the experimental freedom to require further that the magnitudes p_1 and p_2 are nearly equal within a narrow range. Moreover, that magnitude should not be too high, say, in the 2 – 5 GeV range. In so doing we can maximize the contribution from $c\bar{c}$ pair creation to the formation of $D\bar{D}$. There are several stages of reasoning involved here, which we now describe.

The possible parton types are q and c , where q denotes u , d , or g collectively. Let the flavor labeling not be encumbered by concerns about quark or antiquark differences. We postpone our consideration about the s quark until later. The possible hadronization processes are fragmentation (F) and recombination (R), for which $k > p$ in F , but $k < p$ in R . Thus for the production of D there are four possible processes: $F(q \rightarrow D)$, $F(c \rightarrow D)$, $R(q \rightarrow D)$, and $R(c \rightarrow D)$. At high collision energies there are so many hard subprocesses [2] that there are enough transversely moving partons to make recombination competitive with fragmentation in the formation of D in \mathcal{T}_0 . That is not the case in pp or pA collisions. In fact, for any given momentum p of D in \mathcal{T}_0 , it is more favored to recombine two lower momenta partons to add up to p than to create a higher momentum parton which subsequently decays to p , since the probability of creating high k_T partons falls off as a power $k_T^{-\alpha}$, with $\alpha > 4$. For single-particle inclusive distribution a comparison between the two hadronization processes in the production of particles in \mathcal{T}_0 has been studied quantitatively [5] with the result that

for $p_T < 6$ GeV/c and for large nuclei the rate of hadronization through recombination is at least an order of magnitude higher than through fragmentation. For a pair of correlated particles the R/F ratio of the rates would be squared. Thus we may ignore $F(q \rightarrow D)$ and $F(c \rightarrow D)$ in the following discussion.

Since $m_c \approx 5 m_q$ for constituent quark masses, the momentum fractions x_c and x_q of c and q , respectively, in D are on the average very different, with $x_c \approx 5 x_q$; hence, the recombination function for $c + q \rightarrow D$ is maximum when $\vec{k}_c \approx 5 \vec{k}_q$ in the same direction [6, 10]. For \vec{p}_1 and \vec{p}_2 nearly equal and opposite, the production of $D\bar{D}$ is therefore dominated by the creation first of $c\bar{c}$ pair with $\vec{k}_1 \approx -\vec{k}_2$ followed by recombination with low-momentum q quarks, rather than by the process where a created $q\bar{q}$ pair dictates the momenta of the D mesons. In short, $R(c \rightarrow D)$ is more important than $R(q \rightarrow D)$. In the following we shall focus on the process where $S(\vec{k}_1, \vec{k}_2)$ in (2) describes the hard production of a $c\bar{c}$ pair, and the two H functions represent $R(c \rightarrow D)$.

The only part in the problem that has a firm theoretical footing is the amplitude M for hard scattering in (2), which is calculable in pQCD. Even there, charm production with $k_T \sim 2$ GeV/c is in the grey area of reliability. As mentioned earlier, the parton distribution $F_A(x_a)$ and $F_B(x_b)$ are quite uncertain, but the normalized cumulant $C(\vec{p}_1, \vec{p}_2)$ is insensitive to all of them, including M ; furthermore, we emphasize the misalignment of \vec{p}_1 and \vec{p}_2 , their magnitudes being selected by experimental cuts. Thus the signature we seek depends mainly on $H(k_i \rightarrow p_i)$, which is sensitive to the medium that stands between the creation of $c\bar{c}$ and the detected hadrons $D\bar{D}$. That is just what a good probe should be. It is unfortunate that $H(k_i \rightarrow p_i)$ cannot at this point be calculated precisely in QCD, perturbative or otherwise. However, the discovery of unambiguous experimental signature is more important than having reliable theoretical calculations at this stage. On the basis of reasonable arguments we indicate below what that signature might look like.

The four vectors \vec{k}_i and \vec{p}_i ($i = 1, 2$) are all very close to \mathcal{T}_0 . We consider below only their projections \vec{k}_{iT} and \vec{p}_{iT} on \mathcal{T}_0 . For brevity we shall omit the subscripts T , unless there is confusion. Let the angles among these four vectors be labeled as follows: $\theta_1(\vec{k}_1, \vec{p}_1)$,

$\theta_2(\vec{k}_2, \vec{p}_2)$, $\theta_{12}(\vec{k}_1, -\vec{k}_2)$, and $\phi(\vec{p}_1, -\vec{p}_2)$. For simplicity let the distributions in these angles be represented by Gaussians: $\exp(-\theta_1^2/\lambda_1^2)$, $\exp(-\theta_2/\lambda_2^2)$, $\exp(-\theta_{12}^2/\lambda_{12}^2)$, and $\exp(-\phi^2/\lambda^2)$, respectively. The distribution in ϕ is a Gaussian also because of the convolution theorem, since (2) implies

$$c(\vec{p}_1, \vec{p}_2) \propto \int d\theta_1 d\theta_2 \exp\left(-\frac{\theta_1^2}{\lambda_1^2} - \frac{\theta_{12}^2}{\lambda_{12}^2} - \frac{\theta_2^2}{\lambda_2^2}\right), \quad (6)$$

where $\theta_{12} = \phi - \theta_1 - \theta_2$. Thus if λ_1 , λ_2 and λ_{12} are all small compared to π , then

$$\lambda^2 = \lambda_1^2 + \lambda_2^2 + \lambda_{12}^2. \quad (7)$$

One can improve on these integrations with better knowledge on $S(\vec{k}_1, \vec{k}_2)$ and $H(\vec{k}_i, \vec{p}_i)$, but the result will not differ much from (7), which encapsulates the property that the width in $\vec{p}_1 \cdot \vec{p}_2$ is the rms sum of those in $\vec{p}_1 \cdot \vec{k}_1$, $\vec{k}_1 \cdot \vec{k}_2$ and $\vec{p}_2 \cdot \vec{k}_2$. Since we require $|\vec{p}_1| \approx |\vec{p}_2| \equiv p$, we may write $C(\vec{p}_1, \vec{p}_2)$ as $C(p, \phi)$. Then we have

$$C(p, \phi) = C(p) e^{-\phi^2/\lambda^2}. \quad (8)$$

Alternatively, one can define $\vec{p}_1 = -\vec{p}_2 + \vec{p}_t$ (note the small t), where \vec{p}_t is nearly normal to the trigger axis but still in \mathcal{T}_0 . Thus experimentally, the data on $C(\vec{p}_1, \vec{p}_2)$ can be presented as distributions in $\xi \equiv p_t/p$ for various values of the trigger momentum p . Empirical $C(p, \xi)$ should be sharply peaked in ξ , though not necessarily Gaussian; the width can be represented by λ in (8) in the following discussion.

In order to keep all the quantities in (7) small, p should not be too small; neither should it be too large so that the rate of producing two correlated D mesons does not become too low. The range $2 < p < 5$ GeV/c appears to be reasonable. In that range the c and \bar{c} quarks are beams in the dense medium with momenta k_1 and k_2 , both $< p$, insufficient to give any hope to the validity of pQCD in describing their passages through the medium. Nevertheless, we expect charm quarks in that momentum range to be sensitive to the medium effects and can provide us with useful information.

We now consider the various contributions to (6). Nonzero θ_{12} means that $\vec{K} \equiv \vec{k}_1 + \vec{k}_2 \neq 0$. Nonzero \vec{K} is due to the intrinsic transverse momenta of the partons plus the recoil from

initial-state radiation before the hard subprocess that creates the $c\bar{c}$ pair. We expect $|\vec{K}|$ to be small, and set its average value at 0.3 GeV/c for low k_i and allow it to be higher for higher k_i . Approximating $k_1 = k_2$ and denoting them collectively as k , we have $\cos\theta_{12} = 1 - K^2/2k^2$, and $\theta_{12} \simeq K/k$. Thus for $k > 2$ GeV/c, we have $\lambda_{12} \leq 0.15$. More importantly, λ_{12} is independent of the medium in which the created c quarks will traverse, and will therefore not affect our signature of the medium effect.

Next, we consider the last two terms of (6) due to the H functions in (2), which are the heart of the problem. The two H functions independently describe the hadronization processes from \vec{k}_i to \vec{p}_i , as they proceed along the paths l_1 and l_2 , through the medium in essentially opposite directions in \mathcal{T}_0 from the point of creation of $c\bar{c}$. Since the result we seek concerns the sum $\lambda_1^2 + \lambda_2^2$ in (7), it is equivalent to that due to one c quark traversing the entire path $L = l_1 + l_2$ from one end of the medium to the other in \mathcal{T}_0 , passing through the point of $c\bar{c}$ creation. The transverse expansion of the medium is not rapid. If R is the average radius of the system that is relevant to this study, then when averaged over all possible points of the $c\bar{c}$ creation in \mathcal{T}_0 and over all orientations of the path, the mean path length L of crossing a disc of radius R is $L = 4R/3$. Our consideration is thus reduced to the hadronization of a c quark with initial momentum \vec{k} passing through a slab of the medium of thickness L and emerging as a D meson with momentum \vec{p} .

There are two scenarios to examine. One is that the medium consists of deconfined quarks and gluons, while the other is of high-density hadrons with quarks confined. Let them be referred to as quark matter (QM) and hadron matter (HM), respectively. Of course, they represent two extreme cases, and other scenarios that stand between them are possible. If we know the nature of the signatures for the extreme cases, what happens in the intermediate cases can be estimated by interpolation. Thus for now it is sensible to consider just QM and HM.

1. *Quark Matter.* Being deconfined, the medium cannot support the formation of any hadrons nor the existence of any color flux tubes in it. Thus the c quark that traverses the QM medium remains as a c quark. It may lose momentum and deviate from straightline path,

but the formation of D can occur only after passing through the medium by recombining with a \bar{q} at the exit point. If pQCD were applicable, one could study in detail the effect of multiple scattering as in [11, 12], and determine the degree of energy loss and k_t gain. Hereafter we use k_t to denote parton momentum transverse to \vec{k} . However, for k as low as 2 GeV/c, the reliability of pQCD is questionable. Qualitatively, one expects the radiative energy loss to be reduced for heavy quarks compared to light quarks. We assume that the loss of longitudinal momentum is roughly compensated by the gain in momentum due to recombination so that $p \approx k$. The more important aspect of the problem is the k_t gain. If one regards the result of [11] that takes the LPM effect into account as being valid, then k_t due to gluon radiation is of the order of the color screening mass μ , independent of the number of multiple scatterings. The cumulative effect on k_t due to elastic scatterings depends on whether the random-walk model is valid or the quantum coherence effect is important. In the former case the process is Markovian and k_t would increase with L , while in the latter case it would not. The coherent LPM effect in the longitudinal component is non-Markovian. It has been known that the former is more relevant to conventional large- p_T processes, while the latter is for low- p_T processes. Our $H(c \rightarrow D)$ in the present problem belongs to the latter category. The following experimental facts support the latter.

Exhaustive studies of $h_1 A \rightarrow h_2 X$ inclusive reactions at high energies and low p_T have revealed that, for h_2 in the beam fragmentation region of h_1 , the p_T distribution of h_2 is essentially independent of A [13, 14]. Because of the flavor dependence of the h_2 distribution, the processes can be well interpreted in the parton picture by considering the valence quark that is common in h_1 and h_2 [4, 10, 15]. Take $h_1 = \pi^+$ and $h_2 = K^+$ to be specific. For K^+ with high x_F , it is the high momentum u quark in π^+ that leads to K^+ by recombination. The p_T of K^+ reflects the k_T of the u quark after traversing the target. The independence of $\langle p_T \rangle$ on A implies that there is no k_T broadening due to multiple-scattering effect on the u quark. Specifically, the data of [14] indicate that $\sigma(p_T = 0.5)/\sigma(p_T = 0.3)$ stays essentially unchanged at 0.5 and 0.48 for $A = Cu$ and Pb , respectively, for $p_{\pi^+} = 100$ GeV/c and $p_{K^+} = 80$ GeV/c. Although it is a u quark traversing normal nuclei, whereas our problem

involves a c quark traversing dense QM, the independence of k_t on the path length is likely to be due to a common origin: quantum coherence in low- k_t processes is non-Markovian, so k_t does not increase with L . The same lack of A dependence is found in [13] for $h_1 = p$ and $h_2 = \Lambda$. We emphasize that it is true only at low p_T . Significant A dependence at high p_T is not excluded, such as in the production of massive dileptons in pA collisions [16, 17], where no A dependence is seen until p_T exceeds 2 GeV/c.

On the basis of these arguments we adopt the following position. Firstly, the magnitude of k_t is small, since heavy quark suffers less deflection; we take it to be of order μ , which according to $\mu^2 = 4\pi\alpha_s T^2$ gives $\mu \approx 0.4$ GeV for $\alpha_s = 0.3$ and $T = 200$ MeV. Secondly, k_t is expected to be independent of L , although a gentle increase with L cannot be ruled out on firm theoretical ground. Since the recombination of c with a \bar{q} to form a D after passing through the QM does not increase p_t beyond the k_t gained, we arrive at the result that $\lambda_1^2 + \lambda_2^2 \approx \lambda_{12}^2$. Consequently, we have $\lambda \approx 0.5/p$, where p is in units of GeV/c. It is clear that if we want λ to be small, p should not be small. That is why we have set $p > 2$ GeV/c.

2. *Hadron Matter.* Consider now the scenario where the created $c\bar{c}$ pair find themselves in a densely packed hadronic medium. The recombination of c with \bar{q} and \bar{c} with q take place rapidly, and it is the D and \bar{D} that traverse the HM in opposite directions. As before, the combined effect on \vec{p}_1 and \vec{p}_2 can be represented by a D of momentum p going through a slab of HM of thickness L . Being a low-momentum hadron ($2 < p < 5$ GeV/c) the D interacts strongly with the mainly pionic medium. The number of multiple collisions in L is $\nu = n_\pi \sigma_{D\pi} L$, where n_π is the pion density. The energy dependence of $\sigma_{D\pi}$ is not known, but its magnitude (in the few mb range) is definitely much greater than partonic cross section. Since $\lambda_1^2 + \lambda_2^2$ is proportional to ν , we therefore expect p_t to be larger (compared to the QM case) and to increase significantly with L . Herein lies the major difference between the two medium effects on $\xi = p_t/p$. Since λ_{12} is the same for the two media, the difference does not depend on it.

Putting together the above considerations leads to our suggestion for the signature of

QM vs. HM. Measure $C(p, \xi)$. Plot the ξ dependence for fixed p and determine the mean $\bar{\xi}$. Examine how $\bar{\xi}$ depends on E_T and A . For HM, $\bar{\xi}$ should be large and increase with E_T and A . If, at high enough s , E_T and A , quark matter is created, then $\bar{\xi}$ should drop down to a low value and become essentially independent of E_T and A . This transition from high and increasing $\bar{\xi}$ to low and roughly constant $\bar{\xi}$ is the signature of QM formation. In short, quarks are smaller than mesons; their difference should be revealed in the measurement of $\bar{\xi}$.

It would also be of interest to study the p dependence of $\bar{\xi}(p)$. If $\sigma_{D\pi}$ increase with p , then $\bar{\xi}_{\text{HM}}$ would be constant in p , in contradistinction from $\bar{\xi}_{\text{QM}}(p)$ which decreases with p .

Another interesting problem arises when the recombination of c (\bar{c}) with \bar{s} (s) is considered. Since in QM the hadronization occurs outside the quark phase, the width $\bar{\xi}_{D_s\bar{D}_s}$ for $D_s\bar{D}_s$ correlation should not differ significantly from $\bar{\xi}_{D\bar{D}}$. However, in HM the formation of D_s and \bar{D}_s occurs inside the medium, and because of the suppressed $D_s\pi$ scattering due to the OZI rule at low energy, we expect $\bar{\xi}_{D_s\bar{D}_s} < \bar{\xi}_{D\bar{D}}$. The observation of these differences would add to our understanding of what occurs in these systems.

What is described in this paper is for idealized systems. In reality the system may be much more complicated and the transition of the behavior of $\bar{\xi}$ may be very gradual. If so, it is unlikely that any other signature would be clear-cut, since it is the system itself that is not sufficiently distinctive. Our proposal deals with the nature of the matter probed, independent of other inessential complications, such as the absolute normalization of the charm production rate, the precise value of the initial temperature, or the validity of pQCD. To have a proper theoretical treatment of the problem is essential ultimately, but for now the need for a distinctive experimental signature seems to be more urgent. Even if the suggested signature turns out to be ineffective because of the complexity not considered in this initial investigation, charm correlation should nevertheless reveal much information about heavy-ion collisions not available so far.

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